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by

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INTRODUCTORY SUMMARY

Performance and energy-transfer measurements were obtained on a cylindrical cesium thermionic converter with an electrically heated emitter of vapor-deposited tungsten and a molybdenum collector at a radial spacing of 0.025 cm. From calorimeter data a significant correlation was found for the prediction of emitter electron cooling ΔQ_E and collector electron heating ΔQ_C,

$$\Delta Q_E = I(2.6 + V)$$

$$\Delta Q_C = I(2.6),$$

where I and V are the converter current and electrode voltage. The error component of this correlation in predicting the emitter heat input is 4 percent or less over the operating variable range: emitter temperature 1200° to $1800^\circ C$; cesium reservoir temperature 300° to $400^\circ C$; collector temperature 600° to $700^\circ C$; and current 0 to 14 amp cm^{-2}. Through measurements of the emitter structure heat losses, the cesium vapor thermal conduction, and the electrode radiation heat transfer, it was found that computation of all zero current energy-transfer quantities can be performed with a two-dimensional digital computer heat-transfer code.

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The electron cooling correlation together with the ability to calculate all of the power loss values in a thermionic converter makes it possible to compute the efficiency of a converter having only I-V characteristics and materials properties. This is an extremely important tool for the analyst to use in computing the performance of complicated systems of thermionic converters where there may occur wide variations in the operating variables.

CONVERTER APPARATUS AND PERFORMANCE

The cesium thermionic converter configuration is shown in Fig. 1. This converter has a cylindrical emitter of vapor-deposited tungsten with an effective emitting area of 14 cm^2 that is spaced at 0.025 cm from a molybdenum collector. Two features which make the converter valuable for energy measurements are the collector heat calorimeter and emitter temperature profile instrumentation.

The collector calorimeter, as shown in Fig. 1, is a thick-wall molybdenum cylinder which has located in it many small thermocouples used for measuring the axial and radial temperature profiles. Ten tantalum radiation heat shields are located at the axial ends to reduce axial heat losses to less than 1 watt. Heat is removed at the outer edge of the calorimeter through closely spaced cooling tubes. The total amount of heat removed from the collector is the sum of the heats removed in the collector upper and lower skirts and through the calorimeter to the cooling lines. These values are determined from measured temperature gradients. Calibration experiments were performed on the calorimeter before the converter was installed. It was determined that the collector heat transfer could be determined within ± 35 watts. This would result in a 4 percent error for a total power throughput of 800 watts.

For an accurate measurement of the emitter temperature profile, correlations were developed in a separate experiment by means of which the emitter temperature distribution was determined from the data of four tungsten-rhenium thermocouples located in the emitter walls at four axial positions.

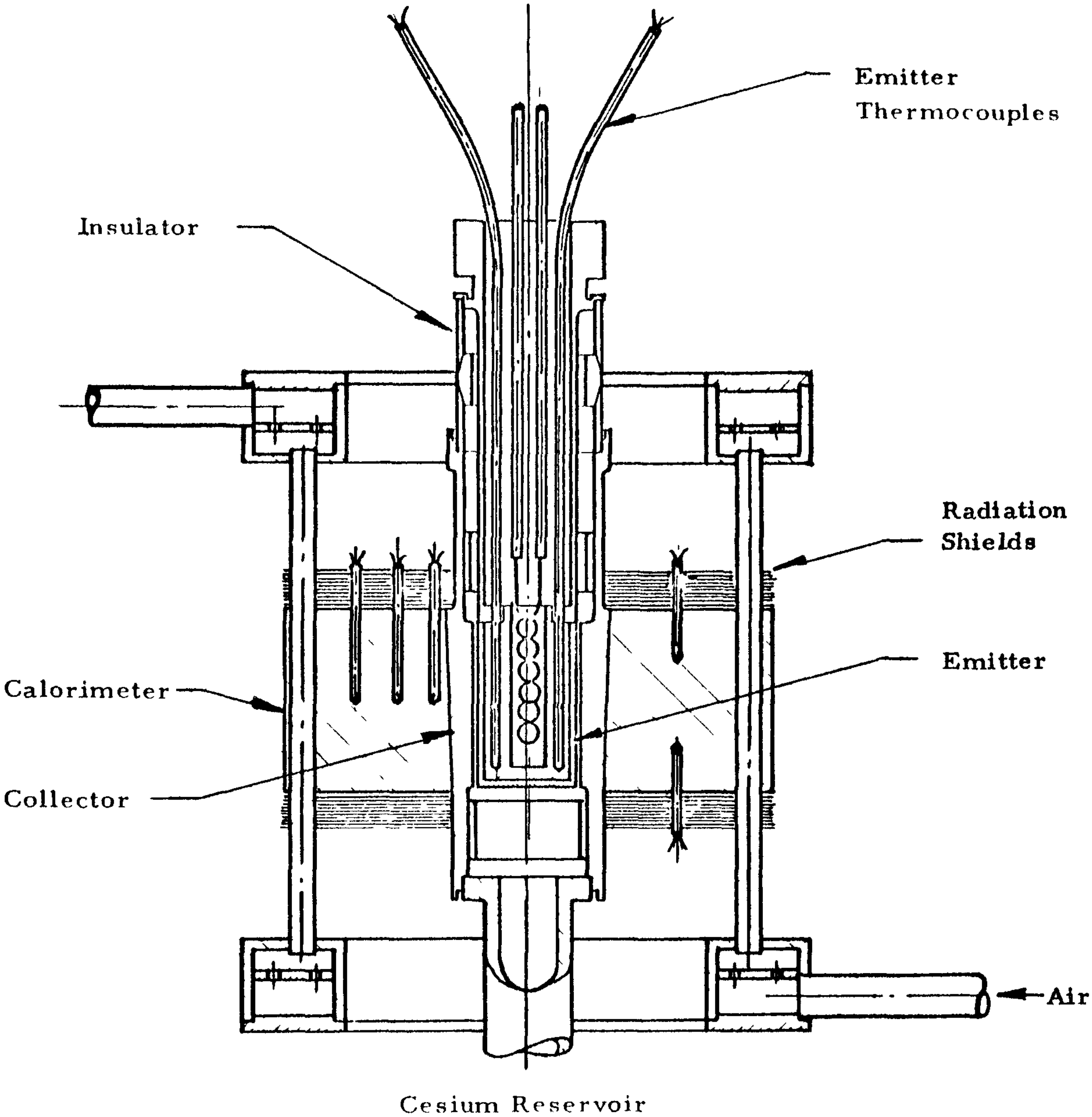

Fig. 1--Mark VI out-of-pile converter

Current-voltage characteristics are shown in Fig. 2 to indicate the type of performance obtained from this converter at $1800^{\circ}C$ for cesium reservoir temperatures ranging from 310° to $390^{\circ}C$. A maximum power output of 11.1 watts/cm^2 was obtained at an average emitter temperature of $1800^{\circ}C$ with a cesium temperature of $350^{\circ}C$ and a collector temperature of $700^{\circ}C$. The maximum efficiency under these optimum conditions was 16 percent. These curves represent a small portion of the total amount of data obtained over the wide range of variables investigated. This range included: emitter temperatures of 1200° to $1800^{\circ}C$, cesium temperatures of 310° to $390^{\circ}C$, and collector temperatures of 600° to $700^{\circ}C$.

EQUATIONS FOR ENERGY CONSERVATION

Energy-conservation equations for the filament, emitter, collector, and calorimeter are derived from the terms depicted in Fig. 3. The electrical power to the emitter filament chamber Q_F is the sum of ac resistance heating and electron-bombardment power. Q_F is dissipated by emitter surface heating Q_E; by the various thermal conduction and radiation losses of the emitter structure and filament, Q_{r1}, Q_{k1}, Q_{r4}, Q_{k4}; and by electrical leakages Q_{IL}, as formalized by Eq. (1);

$$Q_F = Q_E + Q_{r1} + Q_{k1} + Q_{r4} + Q_{k4} + Q_{IL} = Q_E + Q_{EL} + Q_{IL}, \tag{1}$$

where Q_{EL} is the sum of all the emitter structure and filament thermal losses.

The energy leaving the emitter surface goes to collector heating Q_C to provide electrons with an energy that will be dissipated in the emitter lead and the load IV, and to supply energy leakage from the plasma at the ends of the cylindrical interelectrode space, Q_{PL}, or

$$Q_E = Q_C + IV + Q_{PL}. \tag{2}$$

Equations (3) and (4) account for the heat to the collector surface Q_C and the heat to the calorimeter inner surface Q_C':

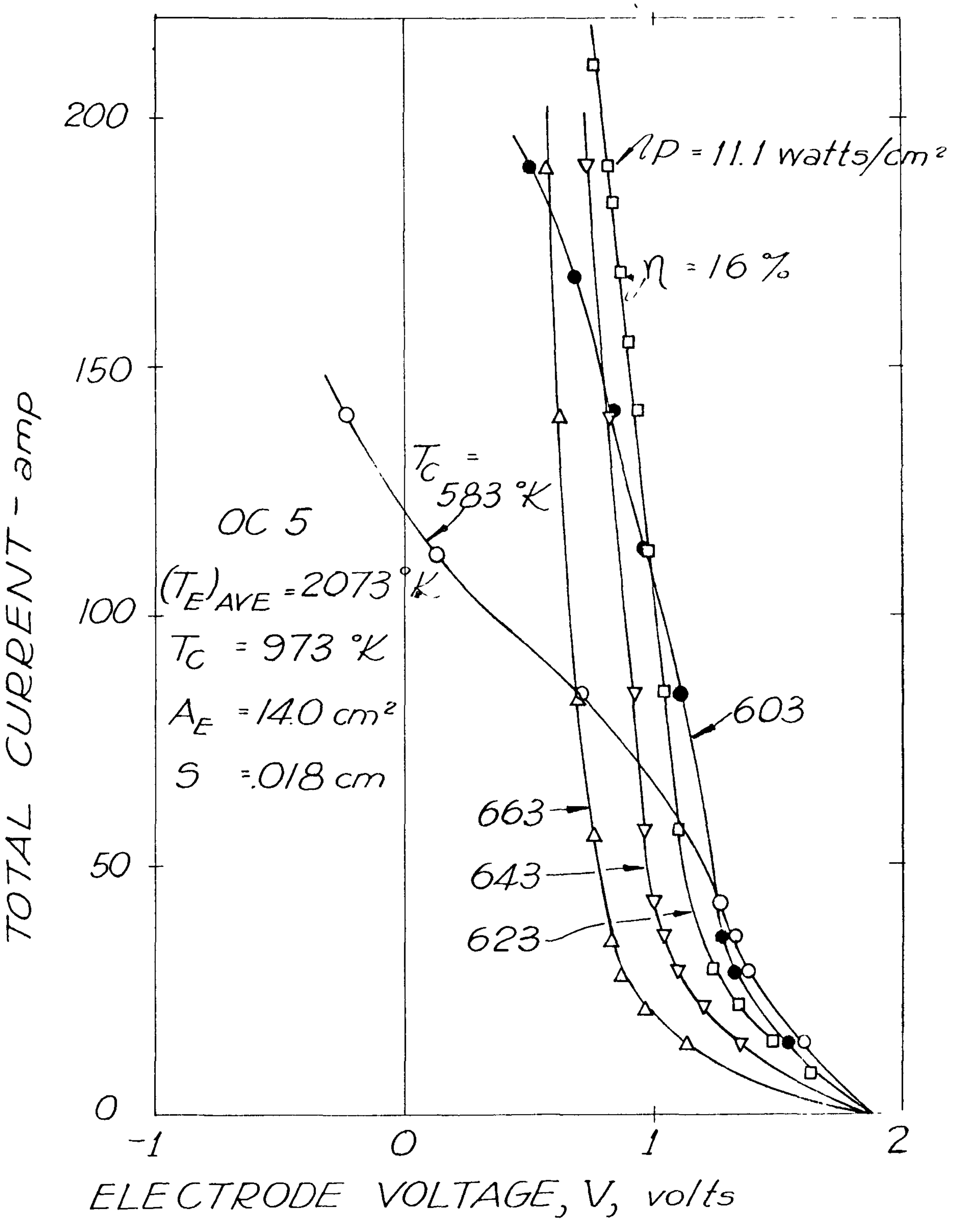

Fig. 2--Current-voltage characteristics

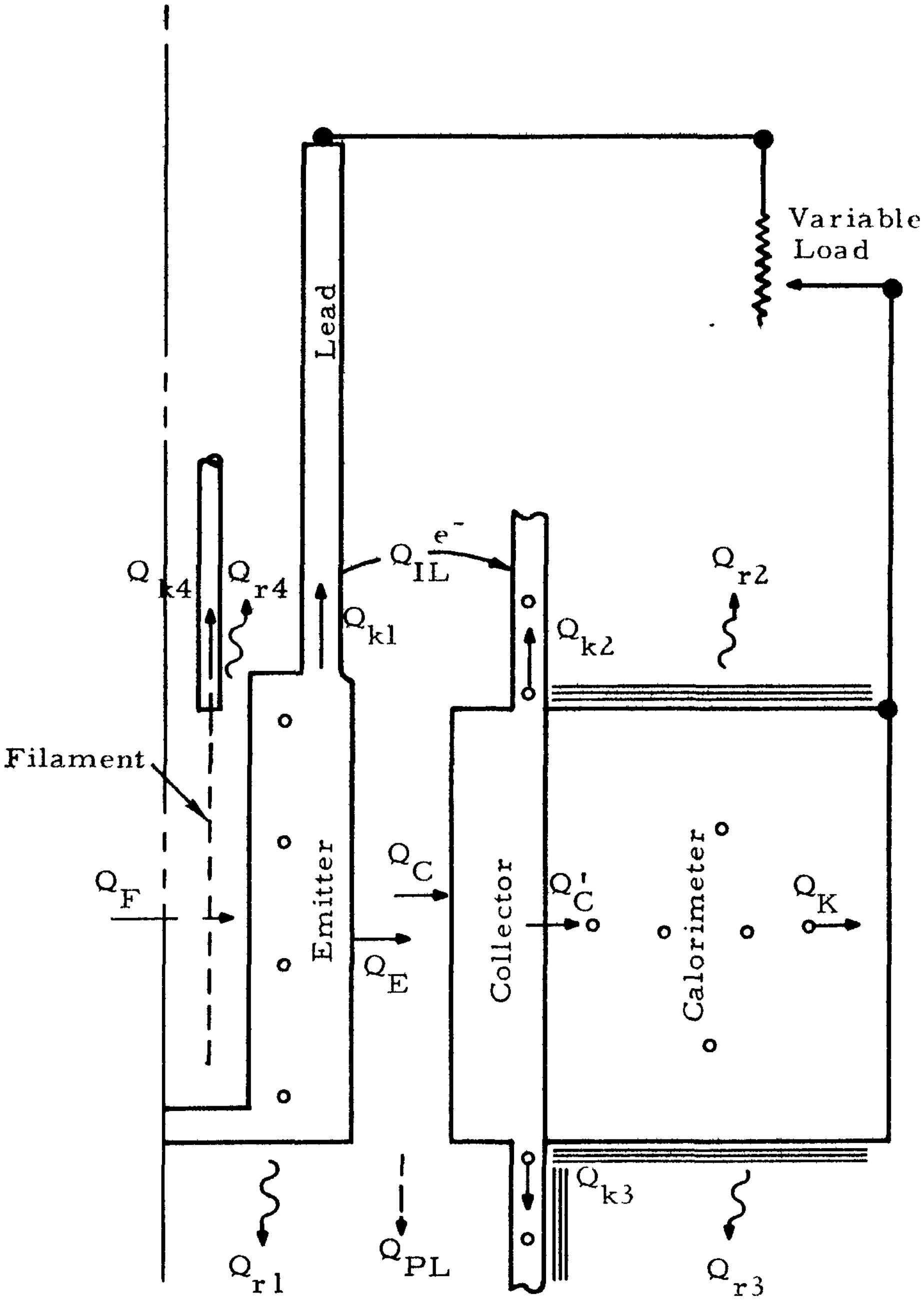

Fig. 3--Terms for energy conservation on converter components

$$Q_C = Q_C' + Q_{k2} + Q_{k3} , \tag{3}$$

$$Q_C' = Q_K + Q_{r2} + Q_{r3} . \tag{4}$$

From calorimeter-calibration experiments, it was found that Q_{r2} plus Q_{r3} is much less than Q_K, and can be neglected since their values are well within the experimental errors of determining Q_K. Under this consideration, Q_C reduces to

$$Q_C = Q_K + Q_{k2} + Q_{k3} . \tag{5}$$

For each experimental point, Q_K, Q_{k2}, and Q_{k3} are calculated from measured temperature gradients and literature values of the material thermal conductivity,[1] and therefore Q_C is a measured quantity through Eq. (5). Experimental values of Q_F are accurately measured to within about 1 percent. The power dissipated in the emitter lead and the load IV is also a measured quantity within about 1 percent accuracy. The remaining unknown values are Q_E, Q_{EL}, Q_{IL}, and Q_{PL}. Experimentally, Q_{IL} is inseparable from IV and is therefore eliminated from all succeeding equations. If Eqs. (1) and (2) are combined,

$$Q_{EL} + Q_{PL} = Q_F - (Q_C + IV) . \tag{6}$$

Since all the terms on the right-hand side of Eq. (6) are measured, the sum of Q_{EL} and Q_{PL} is also a measured quantity. With these terms separately unknown, Q_E from Eq. (2) also remains unknown.

The quantities of emitter electron cooling and collector electron heating are derived from subtracting Q_E and Q_C at zero current from values of Q_E and Q_C at non-zero currents:

$$\Delta Q_E = (Q_E)_I - (Q_E)_{I=0} , \tag{7}$$

$$\Delta Q_C = (Q_C)_I - (Q_C)_{I=0} . \tag{8}$$

It is noted that to call the quantities given in Eqs. (7) and (8) electron cooling or heating is actually a misnomer since ion currents and resonance radiation from the plasma may also contribute to these quantities.[2]

Values of ΔQ_C are directly measured, but ΔQ_E can only be determined by combining Eqs. (2), (7), and (8):

$$\Delta Q_E = \Delta Q_C + IV + \Delta Q_{PL} \ , \tag{9}$$

where ΔQ_{PL} is definded in a similar manner as in Eqs. (7) and (8). Because the ratio of the plasma end areas to the emitter area is very small, it is assumed that ΔQ_{PL} can be neglected in the following analysis of the experimental data. Hence, under that assumption, ΔQ_E is a measured quantity through Eq. (10) since ΔQ_C and IV are experimentally determined:

$$\Delta Q_E \cong \Delta Q_C + IV \ . \tag{10}$$

ENERGY-LOSS MEASUREMENTS AND CALCULATIONS AT ZERO CURRENTS

The total power input to the emitter filament chamber is either dissipated as thermal loss or is converted into electrical power delivered to the load. At zero-current operation, therefore, all of the power input is dissipated as energy loss. The energy quantities measured at zero current are the total power input to the filament chamber Q_F, the power intercepted by the collector Q_C, and the cesium thermal conduction from the emitter to the collector. In Table 1 the data for a single test point are shown along with computed loss values. Heat losses from other than the emitter surface are Q_F minus Q_C, which for this case is 200 watts. These emitter structural losses are the sum of the thermal radiation from the emitter end, the thermal conduction in the emitter lead, the thermal radiation from the filament chamber, and the thermal conduction from the filament leads. This total value was calculated with an IBM-7090 digital computer to be 189 watts, which is a close comparison to the 200-watt loss experimentally determined.

Table 1

MEASURED AND CALCULATED LOSS VALUES
FOR TEST POINT 18, CONVERTER OC-5

Measured Data

Q_F	469 watts
Q_C	269 watts
I	Zero
T_E	1800°C
T_C	700°C
T_{Cs}	350°C
$Q_{EL} = Q_F - Q_C$	200 watts

$Q_{EL} = Q_{r1} + Q_{k1} + Q_{r4} + Q_{k4}$

Computer Results

Q_{r1}	47 watts
Q_{k1}	102 watts
$Q_{r4} + Q_{k4}$	~ 40 watts
$(Q_{EL})_{Calc}$	189 watts
Cesium thermal conduction (determined experimentally)	51 watts
Heat transferred by radiation	269 - 51 = 218 watts
Electrode effective emissivity	0.157
Emitter emissivity (from previous experiment)	0.349
Collector emissivity	0.222

Cesium thermal conduction between the converter electrodes was previously determined experimentally at 51 watts, which compares closely to values predicted by Kitrilakis and Meeker.[3] The heat transferred by radiation between the electrodes is 218 watts, which is the difference between the collector heat and the cesium thermal conduction. From the radiation heat, the interelectrode effective emissivity is calculated to be 0.157. The emitter total emissivity is known from previous experiments to be equal to 0.349 at an emitter temperature of 1800°C. There results a collector emissivity of 0.222. It may be noted at this point that it is possible to predict analytically all of the energy-transfer quantites observed for a zero-current case.

ENERGY MEASUREMENTS AT NON-ZERO CURRENTS

Energy measurements were made over the same range of operating variables that the performance-mapping experiments covered. This range included: emitter temperature of 1200° to 1800°C, cesium reservoir temperature of 300° to 400°C, collector temperature of 600° to 700°C, and current of zero to 15 amp/cm^2 (where possible). A few typical examples of the energy measurements are shown in Figs. 4 and 5, where the values of Q_F, Q_C, IV, and (Q_C + IV) are shown as a function of converter current density. Both of these examples are at an emitter temperature of 1800°C and a collector temperature of 700°C. The difference between the operating conditions of Fig. 4 and Fig. 5 is the cesium reservoir temperature. The "collector electron heating" and "emitter electron cooling" energies are determinable from these data and from Eqs. (7) and (8).

In Figs. 4 and 5 the Q_F curves are found to be not parallel with the (Q_C + IV) curves. The implication of this result is that the sum of ΔQ_{PL} and ΔQ_{EL} is a negative quantity, as would be derived from Eq. (7). It is probable that ΔQ_{EL} is a negative quantity due to the fact that heat is conducted back to the emitter from resistance heating in the emitter lead. The maximum value this could have, however, would be 15 watts when J is 14 amp/cm^2 since the total measured power generated in the stem due to resistance heating is 30 watts. The remainder of the difference, then,

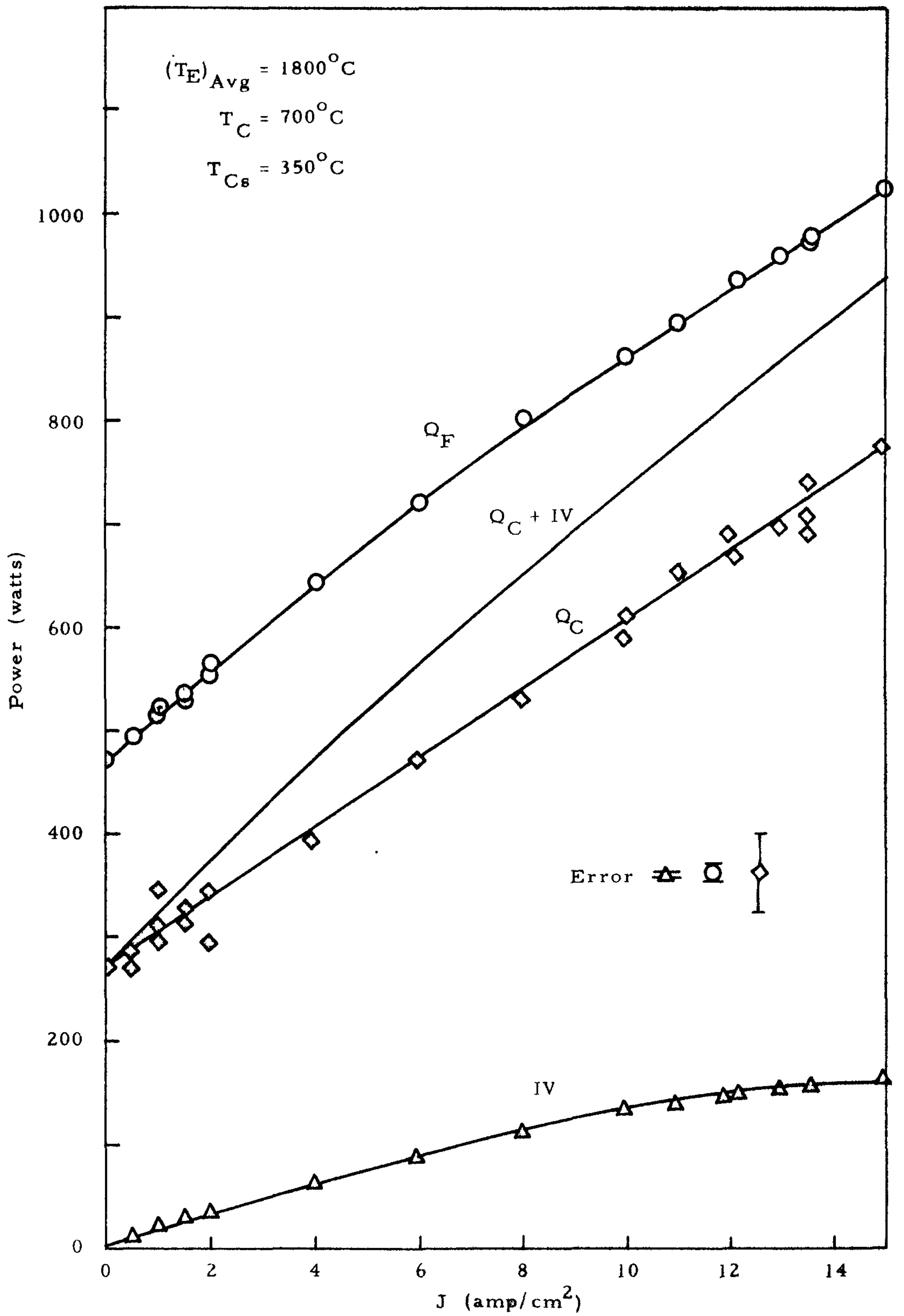

Fig. 4--OC-5 energy measurements at T_{Cs} = 350°C

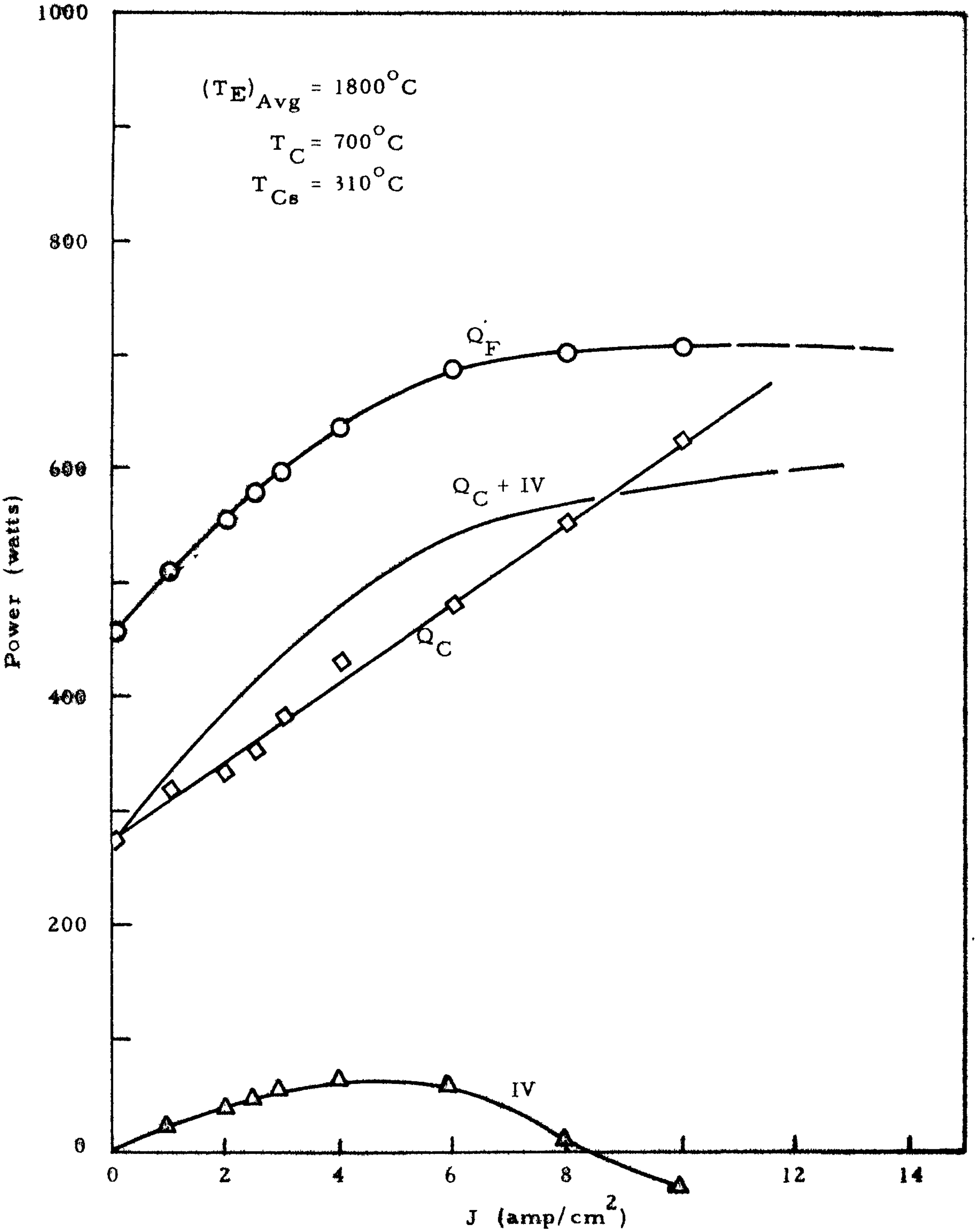

Fig. 5-OC-5 energy measurements at T_{Cs} = 310°C

must be due to changes in emitter temperature distribution, in emitter voltage distribution, or in Q_{PL}. No definite conclusions regarding these differences can be made, however, since the envelope of the calorimeter errors nearly encompasses the remaining differences. A further improvement in the precision of calorimetric measurements would be of value in understanding these differences.

EMITTER ELECTRON COOLING CORRELATION

It is interesting to note that the Q_C curves in Figs. 4 and 5 are linear functions of J and have nearly equal slopes. Furthermore, for all the cases studied it is found that Q_C versus J curves have derivatives of 2.6 ± 0.2 watts/amp. The range of variables covered in the experiment included emitter temperature of 1200° to 1800°C, cesium temperature of 300° to 400°C, and collector temperature of 600° to 700°C.

With the value of dQ_C/dI known to within the errors indicated, it is clear that one may determine with fair accuracy the energy quantities due to emitter electron cooling by substituting the value of ΔQ_C into Eq. (10), obtaining the result:

$$\Delta Q_E = \Delta Q_C + IV = \frac{dQ_C}{dI} I + IV = I(2.6 + V) \ . \tag{11}$$

Emitter electron cooling is therefore predicted from Eq. (11) if performance characteristics in the form of I-V curves are available. It is noted that the uncertainty of $\pm$ 0.2 volt in the slope of Q_C represents only an 8 percent error in determining the collector electron heating. Since the electron cooling of the emitter usually comprises only one-half or less of the total power input to the emitter, the maximum error using this correlation must be less than 4 percent. Under most circumstances, the error would be considerably less.

The correlation is valid within 4 percent accuracy over the operating variable range: emitter temperature of 1200° to 1800°C; cesium reservoir temperature of 300° to 400°C; collector temperature of 600° to 700°C; and current of zero to 14 amp/cm^2.

CONCLUSIONS

Through measurements of emitter-structure heat losses, of cesium vapor thermal conduction, and of the electrode radiation heat transfer, it was found that all the zero-current energy-transfer quantities can be accurately predicted with RAT, a two-dimensional digital-computer heat-transfer code.

The electron cooling correlation, together with the ability to calculate all of the power loss values in a thermionic converter, makes it possible to compute the efficiency of a converter when the I-V characteristics and materials properties are known. This is of special interest to thermionic reactor analysis, since the input to the reactor problem is the amount of fission produced in each of a very large number of cells within the reactor. Apart from the utility of the correlation discovered, the determination of the value of 2.6 volts in the current heating terms is of fundamental interest and invites further study.

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